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# REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188



1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
October 3, 1996

3. REPORT TYPE AND DATES COVERED
Final Progress Report

4. TITLE AND SUBTITLE
Fabrication and Control of Multilayered Superlattice Smart Structures

5. FUNDING NUMBERS
DAAL03-92-G-0360

6. AUTHOR(S)
Vittal Rao

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
University of Missouri-Rolla
1870 Miner Circle
Rolla, MO 65409-0440

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 30130.1-EG-EPS

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

19961025 005

13. ABSTRACT (Maximum 200 words)

This report outlines some of the structural identification and robust control methods developed for smart structural systems. A simple procedure for the shape optimization of distributed sensors is developed. The outputs of these spatially distributed sensors are utilized for the implementation of optimal controllers on the smart structural systems. A structural identification technique is developed by utilizing the multiple parametric measurements provided by the shaped PVDF film sensors. This method generates a minimal state variable representation of the structural system. The outputs of the state variable model are measured by using the distributed sensors. A variety of robust controllers were designed and implemented on the smart structural systems. In this study we have investigated the design of robust controllers by incorporating the performance requirements, robustness against the system uncertainties and the control effort constraints. The robustness properties of the controllers have been verified experimentally.



14. SUBJECT TERMS
Smart structures, distributed sensors and actuators, structural identification, robust control

15. NUMBER IF PAGES
5

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OR REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

# Fabrication and Control of Multilayered Superlattice Smart Structures


Dr. S. Vittal Rao


October 3, 1996


US ARMY RESEARCH OFFICE

**ARO Proposal Number: P-30130-EG-EPS**
**ARO Grant Number: DAAL03-92-G-0360**



University of Missouri-Rolla


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## A. Statement of the Problem Studied

The field of smart structures encompasses several technologies that enable flexible structures to sense and control their own geometric, environmental and structural characteristics to achieve high performance and self diagnostics capabilities. To extend the scope of the parent research award, a graduate student support is provided under the Experimental Program to Stimulate Competitive Research (EPSCoR) program. The objectives of this study are (i) development of distributed sensors and actuators, (ii) structural identification methods using distributed sensors, and (iii) design and implementation of robust controllers for smart structural systems.

## B. Summary of the Most Important Results

**(i) Distributed Sensors and Actuators:** Conventional control design methodologies utilize point sensing and actuation. In recent years there has been considerable interest in the design of spatially shaped distributed sensors for the control of infinite-order structural systems. The smart materials polyvinylidene fluoride (PVDF) and shape memory alloys can be utilized in the development of customized distributed sensors. Sensor shape-optimization techniques are needed for the implementation of optimal control strategies. In this investigation, a method for generating the shape of distributed sensors using finite-dimensional approximations to desired curvature and curvature rate kernels is examined. The output of these spatially distributed sensors is utilized directly as the control signal for suppressing vibrations in finite-order structural systems. We have shown that the desired kernels can be generated directly from finite element models of distributed structures without generating displacement and displacement-rate kernels. The curvature and curvature-rate kernels are the desired kernels in the development of shape functions for PVDF sensors for the implementation of controllers. This procedure requires covering the entire structure with a customized sensor for each kernel. To alleviate this problem, a sensor is developed which covers a portion of the structure with spatially distributed material and uses an observer for the estimation of the states. The original control algorithm is implemented by using the proposed sensor and observer. The usefulness of a single, relatively small customized PVDF film sensor along with an observer to provide full state-feedback information for the entire structure is examined. The complexity and performance of the proposed control schemes are compared with the original distributed sensor implementation.

**(ii) Structural Identification Methods:** A system identification technique for the derivation of minimal, continuos time state variable models for multivariable smart structural systems is developed. This structural identification technique is based on the measurement of eigenvalues and eigenvectors of the structure. Two sensors are required for each mode included in the structural system model. Unlike conventional identification techniques, the relatively large number of sensors simplifies the identification process making it ideal for systems with several inputs and outputs. Additionally, the identification technique allows the implementation of multi-input multi-output full state feedback controllers with simple analog hardware. The amount of hardware required for the implementation of an analog linear quadratic regulator is significantly reduced from standard control implementation methods and it also retains the stability margins. An experimental procedure is developed for the measurement of eigenvalues and eigenvectors of a lightly damped structural system. A priori knowledge of the structural system eigenvalues and a specifically formulated sensor array simplify the identification procedure. The identification procedure requires steady state structural excitation only at the resonant frequencies of interest. The states of the resulting state space model correspond directly to the measured outputs allowing for the analog implementation of full state feedback controllers. The amount of experimental data required and the computational effort involved in the modeling of multivariable systems is significantly reduced. The proposed method is successfully implemented on a multivariable smart structural test article.

**(iii) Design and Implementation of Robust Controllers:** In recent years there has been a considerable interest in the design and implementation of active robust controllers for smart structural systems. The performance of these systems is often limited by the amount of available control force and it is therefore imperative that the design utilize all of the available control effort of the actuators. The control design methodologies should consider the availability of limited control effort of the actuators as well as the robustness issues. The parameter variations, unmodeled dynamics of the system models, presence of disturbances and sensor noise are termed as system uncertainties. In this study we have investigated the design of controllers by incorporating the performance requirements, robustness against the system uncertainties, and the control effort constraints. The performance of smart structural systems is influenced by structural parameter variations, operating conditions and modeling errors. A mathematical model of the smart structural system must include not only the nominal plant, but also the uncertainties which originate from the sources. The first form of uncertainty called as structural uncertainty is due to

variations in natural frequencies, damping ratios, etc. The second type of uncertainty, called unstructured uncertainty, is from unmodeled dynamics such as modes outside of the modeled range, nonlinearities or the other unmodeled characteristics. If specific information is known about the way that uncertainties enter the system, it is advantageous to include this information into the design methodology. In this paper we have presented a method for the incorporation of variations in the natural frequencies in the uncertainty modeling. We have developed a method for accounting the unstructured uncertainty in the robust control design methodology. In order to implement the proposed robust controllers, a two-dimensional distributed structure, called lattice structure, is designed and fabricated. Actuation of the structure is provided by PZT actuators. Two shaped PVDF film sensors were used to measure the displacement of the structure. A mathematical model of the structure is determined using experimental test data. The model is validated using the finite element modeling techniques. The robust controllers have been designed for this structure by incorporating the structured and unstructured uncertainties in the design methodology. The performance of the closed loop system for natural frequency variations is determined experimentally. The robustness properties of the controller are experimentally verified.

## C. List of All Publications and Technical Reports


(1) R. Butler and Vittal Rao, "Optimal Control of Infinite-Order Smart Composite Systems Using Distributed Sensors," *International Journal on Composite Engineering,* Vol. 3, No. 6, pp. 577-589, 1994.

(2) R. Lashlee, R. Butler, Vittal Rao and F. Kern, "Robust Control of Flexible Structures Using Multiple Shape Memory Alloy Actuators," *Journal of Intelligent Material Systems and Structures*, Vol. 5, No. 5, pp. 702-712, Sept. 1994.

(3) R. Butler and Vittal Rao, " A State Space Modelling and Control Method for Multivariable Smart Structural Systems," International Journal on Smart Materials and Structures, Vol. 5, No.4, pp. 386-399, August 1996

(4) Vittal Rao, R. Butler, and W. Zhao, " Robust Multiobjective Controllers for Smart Structures," To appear in the Journal of Reinforced Plastics and Composites, 1996

(5) C. Tebbe, T. Schroeder, R. Butler, V. Rao, and L. Koval, "Modeling and Robust Control of Smart Structures," Paper No. 1919-31, *Proc Smart Structures and Materials,* Albuquerque, NM, SPIE Vol. 1919, pp. 283-297, Feb. 1993.

(6) R. Lashlee, R. Butler, V. Rao and F. Kern, "Robust Control of Flexible Structures Using Multiple Shape Memory Alloy Actuators," *Proceedings of the First IEEE Regional Conference on Aerospace Control Systems,* Westlake Village, CA, May 1993, pp. 798-804.

(7) V. Rao and R. Butler, "Optimal Control of Infinite-Order Smart Composite Structural Systems Using Distributed Sensors," *ARO Workshop on Dynamic Response of Composite Structures,* New Orleans, Aug. 30-Sept. 1, 1993

(8) R. Butler, V. Rao, and L. Koval, "Controller Implementation on Infinite Order Structural Systems Using Distributed Sensors," *Proceedings of 1994 North American Conference on Smart Structures and Materials,* Orlando, FL, February 1994, SPIE Vol. 2190, pp. 358-368.

(9) R. Butler and V. Rao, "State Measurement and System Identification of a Cantilever Beam Using Distributed PVDF Film Sensors," *Proceedings of Symposium on Active Materials and Smart Structures,* Society of Engineering Science Meeting, College Station, TX, October 1994, SPIE Vol. 2427, pp. 65-79.

(10) V. Rao, R. Butler and W. Zhao, "Robust Multiobjective Controllers for Smart Structures, *Fifth International Conference on Adaptive Structures,* Sendai, Japan, December 1994, pp. 163-172.

(11) R. Butler and V. Rao, "Identification and Control of Two-dimensional Smart Structures Using Distributed Sensors," *Proceedings of the 1995 North American Conference on Smart Structures and Materials,* February-March 1995, San Diego, CA, Vol. 2442, pp. 58-69.

(12) R. Butler and V. Rao, "State Space Modeling and Control of MIMO Smart Structures," *Proceedings of the 34th IEEE Conference on Decision and Control,* New Orleans, LA, Dec. 1995, pp. 3534-3539.

(13) R. Butler and V. Rao, "The Incorporation of Structural Uncertainities in a Smart Structural System Identification Technique," *Proceedings of the 1996 North American Conference on Smart Structures and Materials,* February 1996, San Diego, CA, SPIE Vol. 2715, pp. 2-15.

(14) R. Butler, Vittal Rao, and R. Damle, " Design of Robust Controllers for Smart Structural Systems with Actuator Saturation," *Proceedings of the 7th International Conference on Adaptive Structures and Technologies,* September, 1996, Rome, Italy.

(15) MS thesis: Robert Butler, " Optimal Control of Infinite-Order Smart Structural Systems Using Distributed Sensors," University of Missouri-Rolla, 1993

(16) Ph.D. Thesis: Robert Butler, " Identification and Control of Smart Structural Systems Utilizing Multiple Distributed Sensors," University of Missouri-Rolla, 1996

**D. List of all Participating Scientific Personnel:**

| | | | |
|---|---|---|---|
| (1) | Robert Butler | MS | 1993 |
| (2) | Robert Butler | PhD | 1996 |

**E. Report of Inventions:**

NONE